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The OPERA Long Baseline Experiment: Status and First Results

D. Duchesneau (for the OPERA Collaboration)

LAPP, Université de Savoie, CNRS/IN2P3, Annecy-le-Vieux, France

OPERA (Oscillation Project with Emulsion tRacking Apparatus) is an international collaboration between Europe and Asia, aiming to give the first direct proof of tau neutrino appearance in a pure muon neutrino beam, in order to validate the hypothesis for atmospheric neutrino oscillations. The first european long baseline neutrino beam called CNGS is produced at CERN and sent in the direction of the Gran Sasso underground laboratory 730 km away, where the OPERA detector is located. Since 2006 the electronic detector part is fully commissioned and running. Cosmic ray events have been recorded on a regular basis and the first neutrino beam events have been observed in the target elements made of very precise emulsion films and lead sheets during the last run in autumn 2007. This paper reviews the status of the detector, the beam performances, the first results from the neutrino event analysis and the prospects.

1. INTRODUCTION

OPERA [1] is a long baseline neutrino experiment located in the Gran Sasso underground laboratory (LNGS) in Italy. The collaboration is composed of about 200 physicists coming from 36 institutions in 13 different countries. The experiment is a massive hybrid detector with nuclear emulsions used as very precise tracking devices and electronic detectors to locate the neutrino interaction events in the emulsions. It is designed to primarily search for ν_τ appearance in the CERN high energy ν_μ beam CNGS [2] at 730 km from the neutrino source, in order to establish unambiguously the origin of the neutrino oscillations observed at the "atmospheric" Δm^2 scale. The preferred hypothesis to describe this phenomenon being $\nu_\mu \to \nu_\tau$ oscillation. Combining all the present known neutrino data the best fit values of a global three flavour analysis of neutrino oscillations [3] give for $\nu_\mu \to \nu_\tau$ oscillation parameters $\Delta m^2 = 2.39 \times 10^{-3}\,eV^2$ and $\sin^2 2\theta_{23} = 0.995$. The range of allowed values at 3σ is $2.06 \times 10^{-3} < \Delta m^2 < 2.81 \times 10^{-3}\,eV^2$. In addition to the dominant $\nu_\mu \to \nu_\tau$ oscillation in ν_μ beam, it is possible that a sub-leading $\nu_\mu \to \nu_e$ transition occurs as well. This process will also be investigated by OPERA profiting from its excellent electron identification capabilities to asses a possible improvement on the knowledge of the third yet unknown mixing angle θ_{13}.

The ν_τ direct appearance search is based on the observation of events produced by charged current interaction (CC) with the τ decaying in leptonic and hadronic modes. In order to directly observe the τ kinematics, the principle of the OPERA experiment is to observe the τ trajectories and the decay products in emulsion films composed of two thin emulsion layers (44 μm thick) put on either side of a plastic base (205 μm thick). The detector concept which is described in the next section combines micrometer tracking resolution, large target mass together with good lepton identification. This concept allows to reject efficiently the main topological background coming from charm production in ν_μ charged current interactions.

2. DETECTOR OVERVIEW

The OPERA detector is installed in the Hall C of the Gran Sasso underground laboratory. Figure 1 shows a recent picture of the detector which is 20 m long with a cross section of about 8x9 m^2 and composed of two identical parts called super modules (SM). Each SM has a target section and a muon spectrometer.

The spectrometer allows a determination of the charge and momentum of muons going through by measuring their curvature in a dipolar magnet made of 990 tons of iron, and providing 1.53 Tesla transverse to the neutrino beam axis. Each spectrometer is equipped with six vertical planes of drift tubes as precision tracker together with 22 planes (8x8 m^2) of RPC bakelite chambers reaching a spatial resolution of $\sim$1 cm and an efficiency of 96%. The precision tracker planes are composed of 4 staggered layers of 168 aluminium tubes, 8 m long with 38 mm outer diameter. The spatial resolution of this detector is better than 500 μm. The physics performance of the complete

Figure 1: View of the OPERA detector in Hall C of the Gran Sasso Underground Laboratory in May 2007.

spectrometer should reduce the charge confusion to less than 0.3% and gives a momentum resolution better than 20% for momentum less than 50 GeV. The muon identification efficiency reaches 95% adding the target tracker information for the cases where the muons stop inside the target.

The target section is composed of 31 vertical light supporting steel structures, called walls, interleaved with double layered planes of 6.6 m long scintillator strips in the two transverse directions. The main goals of this electronic detector are to provide a trigger for the neutrino interactions, an efficient event pattern recognition together with the magnetic spectrometer allowing a clear classification of the interactions and a precise localisation of the event. The electronic target tracker spatial resolution reaches 0.8 cm and has an efficiency of 99%.

The walls contain the basic target detector units, called ECC brick, sketched in Fig. 2 which are obtained by stacking 56 lead plates with 57 emulsion films. This structure provides many advantages like a massive target coupled to a very precise tracker, as well as a standalone detector to measure electromagnetic showers and charged particle momentum using the multiple coulomb scattering in the lead. The ECC concept has been already succesfully used for the direct observation perfomed in 2000 by the DONUT experiment [4].

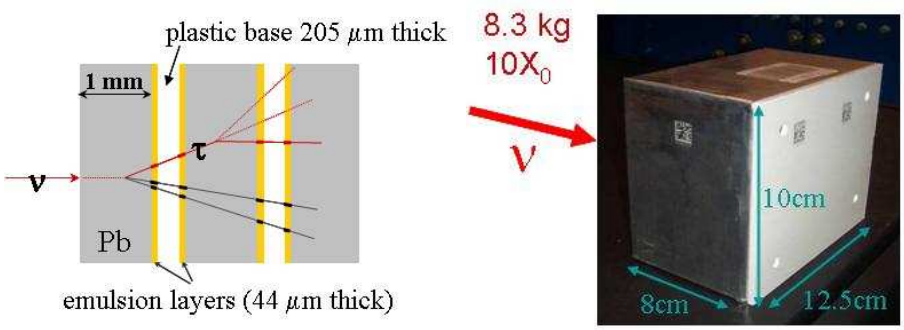

Figure 2: a) Schematic structure of an ECC cell. The decay kink is reconstructed by using four track segments in the emulsion films. b) Picture of an assembled brick. Each brick weights about 8.6 kg and has a thickness of 10 radiation length X_0.

Behind each brick, an emulsion film doublet, called Changeable Sheet (CS) is attached in a separate enveloppe. The CS can be detached from the brick for analysis to confirm and locate the tracks produced in neutrino interactions.

By the time of this conference, 146500 bricks (1.25 kton of target) assembled underground at an average rate of about 700 bricks/day by a dedicated fully automated Brick Assembly Machine (BAM) with precise robotics were installed in the support steel structures from the sides of the walls using two automated manipulator systems (BMS) running on each side of the experiment.

When a candidate brick has been located by the electronic detectors, the brick is removed using the BMS and the changeable sheet is detached and developped. The film is then scanned to search for the tracks originating from the neutrino interaction. If none are found then the brick is left untouched and another one is removed. When a neutrino event is confirmed the brick is exposed to cosmics to collect enough alignment tracks before going to the development. After development the emulsions are sent to the scanning laboratories hosting automated optical microscopes in Europe and Japan, each region using a different technology [5, 6]. This step is the start of the detailed analysis consisting of finding the neutrino vertex and looking for a decay kink topology in the vertex region.

3. THE CNGS BEAM STARTUP

The CNGS neutrino beam [2] is a high energy ν_μ beam optimised to maximise the ν_τ charged current interactions at Gran Sasso produced by oscillation mechanism at the atmospheric Δm^2. The mean neutrino energy is about 17 GeV with a contamination of 2.4% $\bar{\nu}_\mu$, 0.9% ν_e and less than 0.06% of $\bar{\nu}_e$. Using the CERN SPS accelerator in a shared mode with fixed target experiment together with LHC, 4.5x10^{19} protons on target (pot) per year should normally be delivered, assuming 200 days of operation. The number of charged current and neutral current interactions expected in the Gran Sasso laboratory from ν_μ are then about 2900 /kton/year and 875 /kton/year respectively. If the $\nu_\mu \rightarrow \nu_\tau$ oscillation hypothesis is confirmed, the number of ν_τ's produced via charged current interaction at the Gran Sasso should be of the order of 14 /kton/year for $\Delta m^2 = 2.5\mathrm{x}10^{-3}\,\mathrm{eV}^2$ at full mixing.

A first CNGS short run took place in August 2006. The OPERA target was empty at that time but the electronic detectors were taking data. During this run, 319 events correlated in time with the beam and coming from neutrino interactions in the surrounding rock and inside the detector have been recorded. The delivered intensity correponded to $7.6\mathrm{x}10^{17}$ pot, with a peak intensity of $1.7\mathrm{x}10^{13}$ pot per extraction corresponding to 70% of the expected nominal value. The reconstructed zenith angle distribution from penetrating muon tracks was showing a clear peak centered around 3.4° as expected for neutrinos originating from CERN. Details and results can be found in Ref [7].

4. FIRST NEUTRINO EVENTS AND DETECTOR PERFORMANCES

A second CNGS physics run took place in October 2007 with a total of $8.24\mathrm{x}10^{17}$ pot delivered and 369 reconstructed beam related events. Similar selection criteria to the 2006 analysis [7], based on GPS timing systems and synchronisation between OPERA and CNGS, have been used to select events compatible with the CNGS proton extraction time window. The OPERA target was filled with 80% of the first supermodule corresponding to a total target mass of 0.5 kton. Among the selected beam events, 38 were recorded and reconstructed inside the OPERA target for 31.5 $\pm$ 6 expected. Among them, 29 were classified as Charged Current (CC) and 9 as Neutral Current (NC) in agreement with expectation. For each event the electronic detector hits were used to find the most probable brick where the neutrino interaction may have occured. The left part of Figure 3 shows an event display of the first neutrino interaction located in the OPERA detector. The black dots represent hits in the electronic detector. The event is a charged current event with a clear muon track traversing both target and spectrometer sections over more than 18 m. The right part of the figure shows the result of the detailed analysis of the emulsions after scanning the identified brick where a clear reconstructed interaction vertex is visible with two photon conversions compatible with a π° decay.

The extensive study of the recorded events have confirmed the OPERA performances and the validity of the methods and algorithms used which, for example, give impact parameter resolution of the order of a few microns, particle momentum estimation, shower detection for e/π^0 separation. Figure 4 shows the longitudinal and transverse views of another reconstructed event vertex where a clear decay topology similar to what is expected from a τ decay is visible. However, the presence of a prompt muon attached to the primary vertex and the momentum balance in the transverse plane is in favour of a ν_μ^{CC} interaction producing a charm particle.

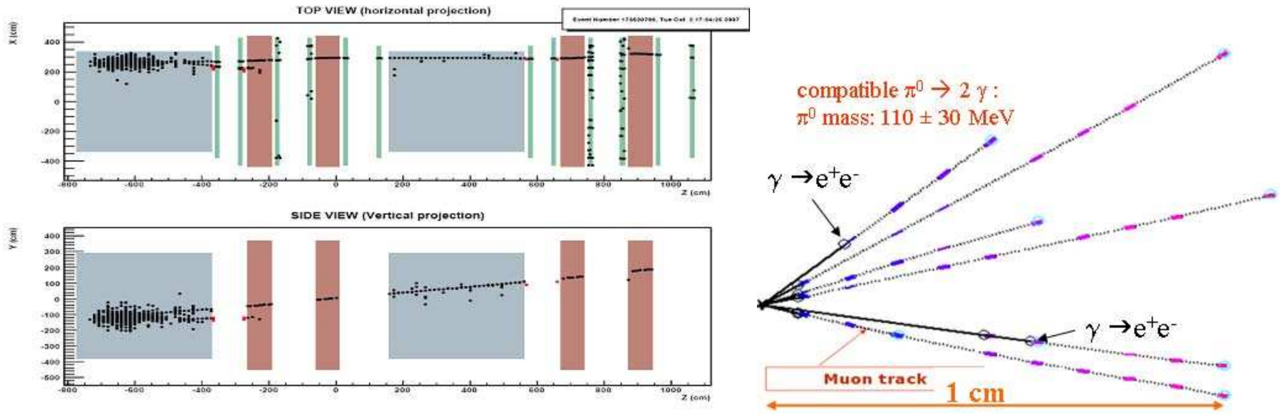

Figure 3: a) Charged current neutrino interaction recorded in OPERA. The event display shows the hits left in the electronic detectors). b) Emulsion reconstruction of the neutrino interaction vertex in the corresponding target brick.

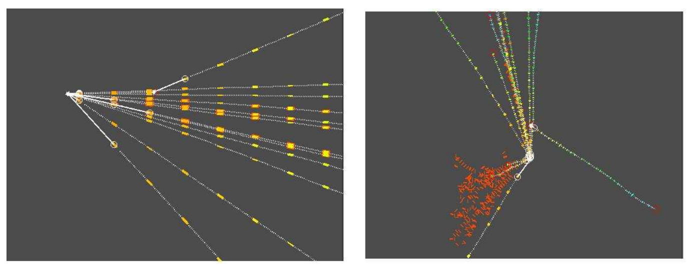

Figure 4: Longitudinal and transverse view of a reconstructed neutrino interaction vertex with a charm decay candidate topology.

5. CONCLUSIONS

The OPERA detector is completed and is now massive with 1.25 kton of lead-emulsion target o ering a huge and precise tracking device. With the cosmic data taking and the rst CNGS neutrino runs in 2006 and 2007, the design goals and detector perfomances were reached and the rst levels of the reconstruction software and analysis tools were validated. The observation in 2007 of 38 neutrino events in the target bricks, the localization and reconstruction of neutrino vertex in emulsions was an important phase which succesfully validated the OPERA detector concept. Having now the full OPERA target, the next important step is the 2008 CNGS neutrino run which started already in June. It is expected to have about $2.28\mathrm{x}10^{19}$ pot in 123 days of SPS running assuming a nominal intensity of $2\mathrm{x}10^{13}$ pot/extraction. This intensity, when reached, should lead to about 20 neutrino interactions/day in the target and eventually the observation of the rst event candidate.
In 5 years of CNGS running at $4.5\mathrm{x}10^{19}$ pot per year, OPERA should be able to observe 10 to 15 events after oscillation at full mixing in the range $2.5\mathrm{x}10^{-3} <$ $m^2 < 3\mathrm{x}10^{-3}$ eV^2, with a total background less than 0.76 events.

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